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Pace Mapping for the Identification of Focal Atrial Tachycardia Origin: A Novel Technique to Map and Ablate Difficult-to-Induce and Nonsustained Focal Atrial Tachycardia

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Pace Mapping for the Identification of Focal Atrial Tachycardia Origin

A Novel Technique to Map and Ablate Difficult-to-Induce and Nonsustained Focal Atrial Tachycardia

Kentaro Hayashi, MD; Shibu Mathew, MD; Christian-H. Heeger, MD; Tilman Maurer, MD; Christine Lemes, MD; Johannes Riedl, MD; Christian Sohns, MD; Ardan M. Saguner, MD; Francesco Santoro, MD; Bruno Reißmann, MD; Andreas Metzner, MD; Karl-Heinz Kuck, MD; Feifan Ouyang, MD

Background—Focal atrial tachycardia (FAT) is extremely difficult to map and ablate when it is difficult to induce and nonsustained. The objective of this study is to evaluate the efficacy of pace mapping in identifying the FAT origin.

Methods and Results—The study included 7 patients with drug-refractory FAT who experienced daily multiple episodes before ablation and presented with difficult-to-induce and nonsustained FAT and a distinct P wave morphology. Pace mapping was systematically performed in the areas of interest using 3-dimensional mapping to match the P wave morphology and paced intracardiac activation sequence recorded from multiple catheters. The anatomic origins of FAT were the right pulmonary vein (PV) in 3 patients, mitral annulus, crista terminalis, tricuspid annulus, and right-sided PV via a posterior conduction of previous PV isolation. In all patients, pace mapping obtained best-matched P wave morphology in $\geq 11/12$ leads of surface ECG at the successful ablation site, and paced intracardiac activation sequence was identical to that of induced FAT. Focal ablation was delivered in 4 patients, including non-PV FAT in 3 and FAT in 1, via posterior gap along the previous right-sided PV isolation, and circumferential right-sided PV isolation was performed in the other 3 patients. No FAT was induced at the end of the procedure. All patients were free of arrhythmias without antiarrhythmic drugs during the 8.4 ± 5.6 -month follow-up.

Conclusions—The combination of paced P wave morphology and intracardiac activation sequence can be used for the identification of FAT origin in patients with difficult-to-induce and nonsustained FAT. (*Circ Arrhythm Electrophysiol.* 2016;9:e003930. DOI: 10.1161/CIRCEP.116.003930.)

Key Words: catheter ablation ■ focal atrial tachycardia ■ mapping ■ nonpulmonary vein focus ■ pace mapping ■ pulmonary vein ■ tachycardia

Focal atrial tachycardia (FAT) is a relatively uncommon form of supraventricular tachycardia that is difficult to treat with antiarrhythmic drugs (AADs). However, with the advent of radiofrequency catheter ablation (CA), this tachycardia can be treated with a high long-term success rate.¹⁻³ The key aspect of successful ablation is to localize the site of the earliest site with and without 3-dimensional (3D) mapping techniques during tachycardia. Although activation mapping remains the cornerstone for identifying the tachycardia origin, the initial P wave morphological information can facilitate ablation procedure. Several P wave algorithms have been developed to identify the origin of tachycardia in most patients with sustained tachycardia.⁴⁻⁸ However, these algorithms may misidentify the FAT origins in patients with diseased atrial muscles or previous linear lesions because of CA or a surgical operation. Furthermore, it is clinically difficult to map and ablate difficult-to-induce and nonsustained FAT

with and without intravenous administration of isoproterenol during ablation. Pace mapping (PM) is generally used to identify ventricular arrhythmia origin and can clinically be highly successful in patients with infrequent ventricular arrhythmias. However, whether the FAT origin can be identified using PM of the atria is unknown. In this study, we aimed to identify the FAT origin using paced P wave morphology and intracardiac activation sequence on 3D mapping during PM in patients with difficult-to-induce and nonsustained FAT.

Methods

Study Population

Between January 2013 and August 2015, 510 patients were referred to Asklepios Klinik St Georg (Hamburg, Germany) for CA of atrial tachycardia (AT). Macro reentry and focal AT were observed in 396 and 114 patients, respectively. Of 114 patients, 7 (6.1% of patients with FAT, 4 men; average age, 43.3 ± 17.5 years) presented as symptomatic,

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WHAT IS KNOWN

- Focal atrial tachycardia is extremely difficult to map and ablate when it is difficult to induce and nonsustained.
- Pace mapping is commonly used in patients with ventricular arrhythmias; however, the origin of focal atrial tachycardia is rarely identified only by pace mapping because activation mapping in conjunction with pace mapping has usually been used.

WHAT THE STUDY ADDS

- Pace mapping may be useful for identifying the focal atrial tachycardia origins by matching P wave morphology and intracardiac atrial activation sequence.
- This maneuver can be used for patients with difficult-to-induce and nonsustained focal atrial tachycardia to improve clinical outcome.

drug-refractory, and nonsustained type with a distinct P wave morphology and frequent daily episodes on Holter electrocardiography (ECG; Figure 1A) and ablated using only PM. In other 107/114 (93.9%) patients, activation mapping was used to guide ablation procedure. All 7 patients had structurally normal hearts as documented by echocardiographic evaluation. Previous ablation was documented in 5 patients, including failed FAT ablation in 1 patient, slow pathway ablation for atrioventricular nodal reentrant tachycardia in 2 patients at another center, and circumferential pulmonary vein isolation (PVI) because of the misdiagnosis of atrial fibrillation based on irregular heart rate on Holter ECG in the remaining 2 patients. The present study is a retrospective analysis and was approved by the local ethics committee.

Electrophysiology Study

AADs were discontinued ≥ 5 half-lives before CA. All patients provided written informed consent to undergo an electrophysiological study in the fasting state: 5 under mild sedation and 2 without sedation. Two 8-pole catheters with interelectrode space (the initial part of 2–10–2 mm, the remaining part of 5 mm) were positioned in the coronary sinus (CS) and at the His-bundle area. When pulmonary veins (PVs) were suspected to be the FAT origin, an additional 10-pole circular mapping catheter was inserted into the PV through an 8.5-F long sheath (SL1) using the modified Brockenbrough technique. Twelve-lead surface ECGs and intracardiac electrograms were recorded simultaneously using a digital multichannel system (EP-WorkMate; St Jude Medical, St Paul, MN) and filtered at 30 to 500 Hz for bipolar and at 0.05 to 500 Hz for unipolar electrograms. If clinical arrhythmias failed to occur spontaneously, programmed stimulation was performed at 2 basic drive cycle lengths (CLs) with 2 extra stimuli until the refractory period and burst pacing with a shortest CL of 230 ms at the right atrium (RA) and proximal of CS. If clinical arrhythmia was not inducible at baseline, intravenous isoproterenol infusion (1–4 $\mu\text{g}/\text{min}$) and interruption of sedation were administered to provoke clinical arrhythmias. The P wave morphology on surface 12-lead ECG and intracardiac atrial activation sequence recording from >2 catheters during spontaneous or induced nonsustained FAT were analyzed.

3D Electroanatomical Mapping and PM

Anatomic reconstruction of the atrium was initially performed using a 3D electroanatomical mapping system (CARTO; Biosense Webster, Diamond Bar, CA) during sinus rhythm. Mapping in both atria was performed using a 7.5-F D-curve catheter with a 3.5-mm open-irrigated-tip electrode (Navistar ThermoCool catheter with unidirectional curve; Biosense Webster). The paced P wave morphology

and intracardiac atrial activation sequence were compared with those during AT. Bipolar PM was systematically performed at the areas of interest based on the algorithm of P wave morphology of the tachycardia on surface ECG.^{5,6} Later, we paced the expected area and surrounding area according to specific structure (eg, PV, CS, mitral annulus, tricuspid annulus, and crista terminalis). If one of them obtained a good paced match of the P wave and atrial activation sequence, denser PM was performed close to the good paced match site to obtain best-paced match site. The sites with PM were tagged and labeled on the CARTO map. PM was always performed with minimal output (voltage, 2–10 mV; pulse duration, 0.5–2 ms) and CL similar to clinical AT-CL to avoid far-field capture of adjacent structures, which can result in variations of paced P wave morphology or atrial activation sequence because of conduction delay.

P wave morphology on 12-lead ECG was assessed as previously described.^{5,6} The P wave analysis was performed during periods of atrioventricular block or long pause after ventricular pacing at a paper speed of 50 mm/s. P wave morphology in the 12-lead ECG was matched manually by 2 trained electrophysiologists. P waves were described based on the deviation from baseline during the T–P interval as (1) positive if there was a positive deflection from the isoelectric baseline, (2) negative if there was negative deflection, (3) biphasic if there were both positive and negative deflections from baseline, and (4) flat if there were no deflections from baseline. We attempted to match the captured P wave morphology at each site during pacing with the P wave morphology during clinical AT as assessed from P wave configurations, amplitude, and duration. Additionally, the intracardiac atrial activation timing and activation sequence recording from multiple catheters during AT and atrial pacing were measured, and deviations between AT and atrial pacing were compared at every paced site. Briefly, the activation time and sequence were recorded from >2 diagnostic catheters, which were stably positioned at the His region, CS, and in some cases, within the PV (eg, time between atrial recording in the proximal His bundle and distal CS). A stable reference from distal CS was used to measure the intracardiac atrial activation time and the sequence of atrial depolarization during tachycardia and PM, which was performed using the ablation catheter with minimal output and CL similar to clinical AT-CL. We paid attention to not only activation sequence and time interval between 2 catheters but also the morphology and polarity of bipolar potential in diagnostic catheter manually to improve diagnostic performance. The best-paced site was defined as the paced P wave, and the paced intracardiac activation sequences were identical/similar to those during AT.

Radiofrequency CA

CA in both atria was performed using the catheter with a 3.5-mm open-irrigated-tip electrode (Navistar ThermoCool; Biosense Webster) in combination with RF generator (Biosense Stockert 70; Stocker GmbH, Freiburg, Germany). The CA target of FAT origin was defined as best-paced site if the tachycardia was not inducible within 30 minutes. Focal ablation was delivered at the origin in patients with non-PV FAT or at the conduction gap in patients with previous circumferential PVI. Circumferential ablation was performed in patients with FAT originated from PV and without previous PVI. In patients with PV FAT, the ablation end point was complete PV antrum isolation with entrance and exit block. Irrigated radiofrequency energy was delivered with a target temperature of 45°C, maximal power limit of 30 W, and an infusion rate of 20 mL/min. After successful ablation, intravenous administration of isoproterenol and pacing maneuvers were repeated to reinduce clinical ATs.

Acute success was defined as (1) absence of spontaneous or provoked clinical AT at the end of the procedure and (2) absence of the atrial tachyarrhythmia on 48-hour postablation ECG monitoring without AADs.

Statistical Analysis

Continuous variables are presented as mean \pm SD, whereas categorical values are presented as absolute values and percentages. Only descriptive statistics are provided.

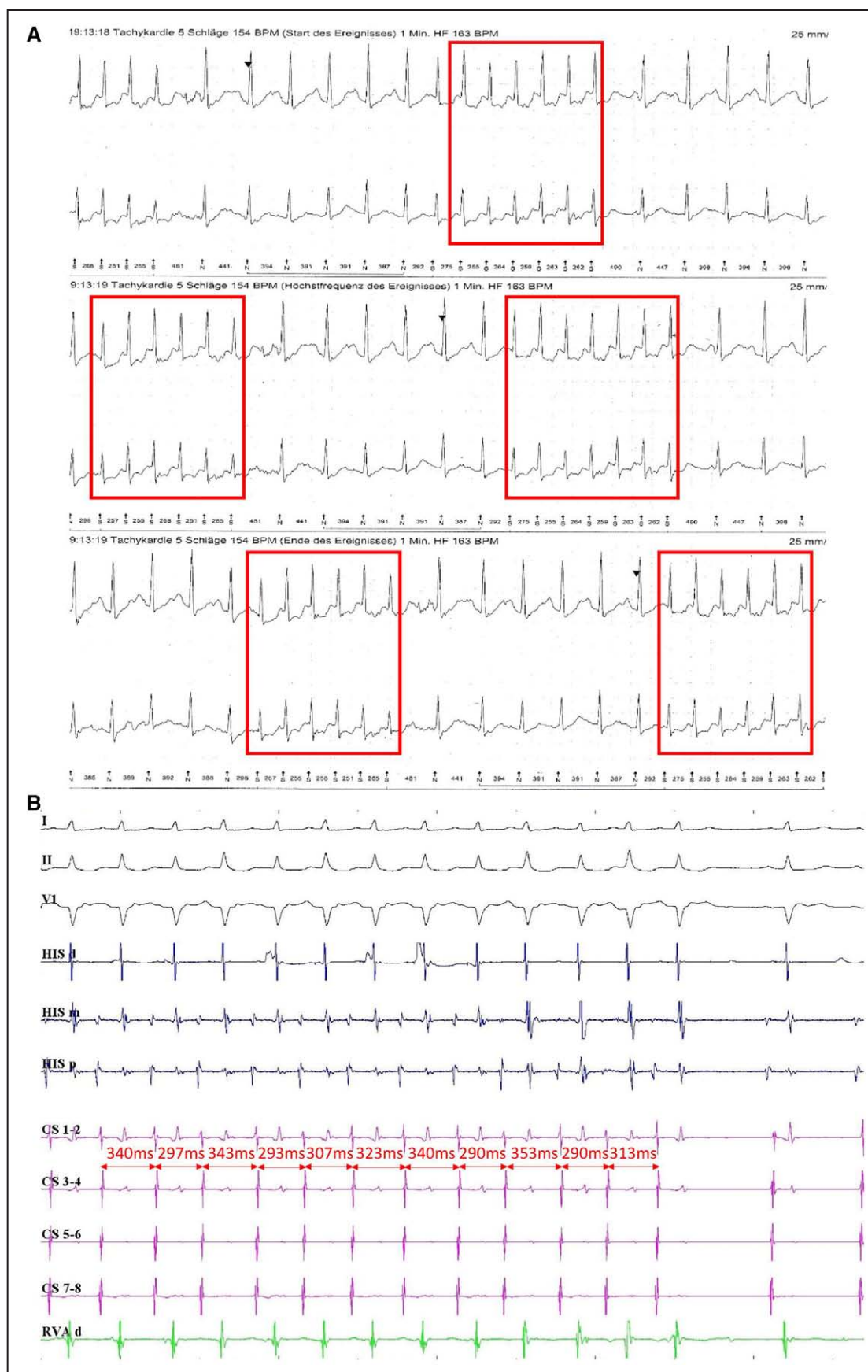


Figure 1. **A**, (Patient no 2): Holter ECG showing multiple short runs of atrial tachycardia. **B**, Intracardiac recording showing nonsustained atrial tachycardia with a variable cycle length.

Table 1. Clinical and 12-Lead ECG Characteristics

	Age, y	Sex	Longest sustainment of FAT, s	CL of FAT, ms	FAT Variable, Range	12-lead ECG II Morphology	12-lead ECG aVL Morphology	12-lead ECG V1 morphology
Patient no 1	25	F	7	312	290–353	Positive	Bifid positive	Negative
Patient no 2	36	F	10	350	322–358	Positive-flat	Flat-negative	Flat-positive
Patient no 3	47	M	2	348	322–368	Positive	Flat	Positive-negative
Patient no 4	23	M	5	492	468–512	Positive	Positive-negative	Bifid positive
Patient no 5	51	M	5	410	386–422	Flat	Flat-positive	Bifid positive
Patient no 6	47	M	3	362	345–380	Negative	Flat	Negative
Patient no 7	74	F	2	554	546–586	Bifid positive	Negative	Bifid positive

CL indicates cycle length; F, female; FAT, focal atrial tachycardia; and M, male.

Results

Clinical and Electrophysiological Characteristics

Clinical symptoms were palpitation in 5 patients and exercise-induced dyspnea in 2 patients. Continuous recording of 24-hour ECG showed daily attacks in 3 patients (Figure 1A, patient no 2). All patients were refractory to 1 to 3 AADs.

FAT was induced with difficulty in all 7 patients. Tachycardia was not initiated by atrial programmed pacing, and all patients required isoproterenol infusion to induce tachycardia, which presented as nonsustained AT with a variable CL in all 7 patients (Figure 1B, patient no 2 and Table 1). A discrete P wave was observed on 12-lead ECG in all 7 patients. The clinical and P wave characteristics in 12-lead ECG are shown in Table 1, and the electrophysiological characteristics of clinical FAT are shown in Table 2.

Paced P Wave Morphology and Intracardiac Activation Sequences

Anatomic mapping was successfully achieved with a mean of 56.9 ± 20.2 points. An area of low amplitude (<0.5 mV) in left atrium (LA) was found in patients no 5 and no 7, respectively, with 1 patient previously having undergone circumferential PVI. Based on P wave morphology, PM was performed at 5 to 16 sites during LA FAT and in 8 to 17 sites during RA FAT. PM obtained best-matched P wave morphology on 12-lead ECG in 12/12 leads in 2 patients, 11/12

in 4 patients, and 11/11 in 1 patient because of noise on the precordial V5 lead.

In 3 patients (patients no 1, no 2, and no 6) with non-PV FAT, the induced tachycardias had maximal durations of 10 s (3–10 s). PM in the area of interest identified the best-paced site at the superior crista terminalis (patient no 1), anterior mitral annulus (patient no 2), and inferior-lateral tricuspid annulus (patient no 6). No low-voltage area in the atrium area of interest was found in these 3 patients. At the best-paced site, the paced P wave morphology of 12-lead ECG was matched to the clinical P wave morphology in 11/12 leads (patient no 1; Figure 2A and patient no 6) and 11/11 leads (patient no 2; Figure 3A). No significant delay from stimulus to P wave onset was observed in these 3 patients. Paced intracardiac activation sequence obtained from His and CS catheter was the same as the sequence of the clinical FAT, and no deviation from the clinical tachycardia was observed (Figures 2B and 3B). After extensive mapping, FAT was not induced in all 3 patients in whom the earliest activation preceding the P wave onset during clinical AT could not be evaluated.

In 4 patients with PV origin (patients no 3–5 and no 7), the induced tachycardias had a maximal duration of 5 s (2–5 s). In 3 patients without previous circumferential PVI, PM in LA revealed that the best-paced match was at the anterior ostium of the right inferior PV (patient no 3), posterior ostium of the right superior PV (patient no 4), and inferior ostium of

Table 2. Electrophysiological Characteristics of Clinical FAT and Ablation Procedures

	Origin of FAT	Low-voltage area in atrium of interest	Type of ablation	Number of pace mapping site	Precedence of the local potential to P wave onset, ms	Deviation of paced intracardiac activation sequence from clinical FAT, ms	Paced match score of PPM
Patient no 1	CT superior	–	Focal	8	NA	0	11/12
Patient no 2	MA anterior	–	Focal	10	NA	0	11/11
Patient no 3	RIPV anterior	–	PVI	12	–40	0	11/12
Patient no 4	RSPV posterior	–	PVI	9	–25	0	11/12
Patient no 5	RPV posterior gap	+	Focal	5	NA	NA	12/12
Patient no 6	TA lateral	–	Focal	17	NA	0	11/12
Patient no 7	RIPV floor	+	PVI	16	NA	NA	12/12

CT indicates crista terminalis; FAT, focal atrial tachycardia; LA, left atrium; MA, mitral annulus; NA, not available; PPM, P wave pace mapping; PVI, pulmonary vein isolation; RIPV, right inferior pulmonary vein; RSPV, right superior pulmonary vein; and TA, tricuspid annulus

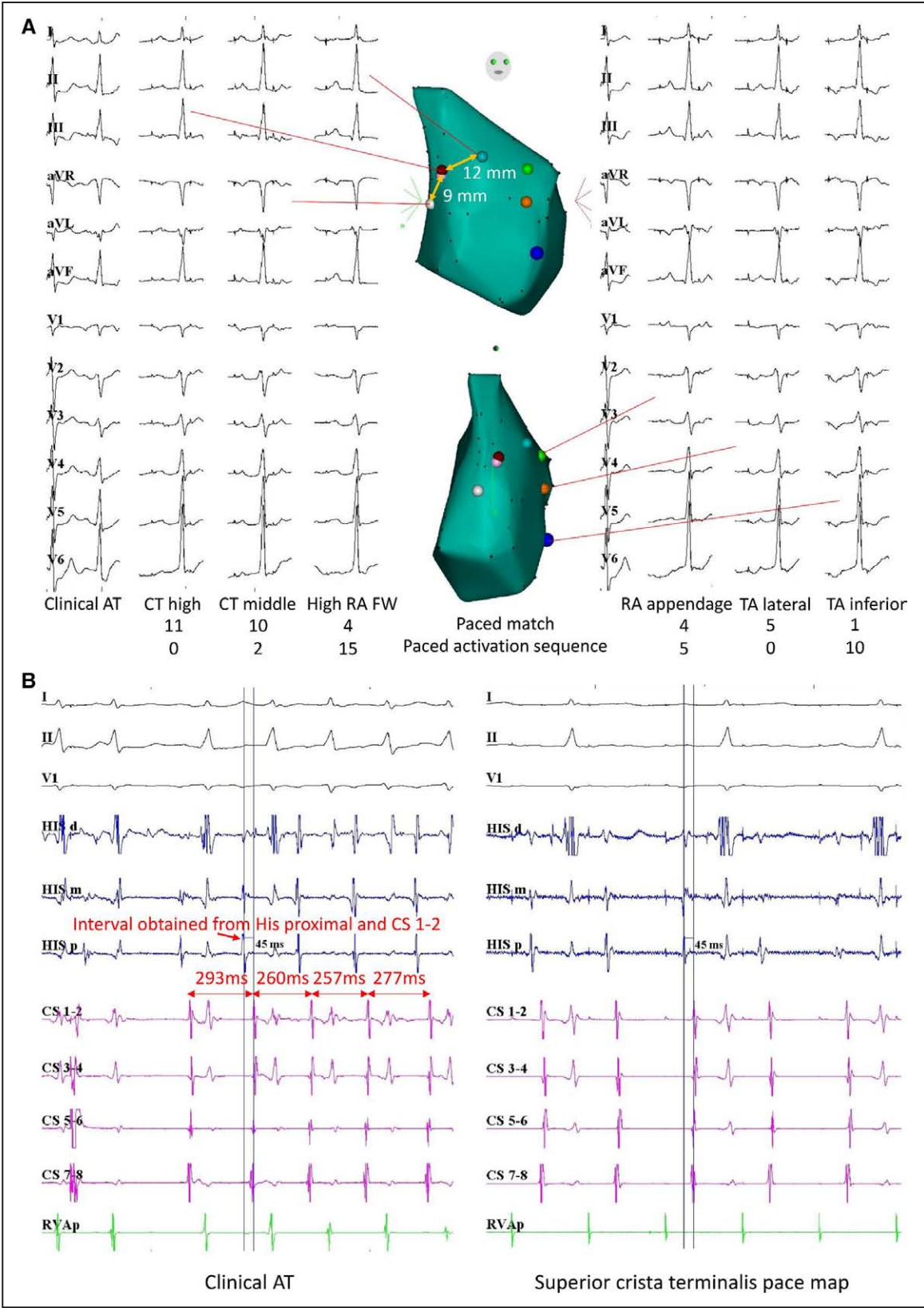


Figure 2. A, (Patient no 1): Comparison of P wave morphology during FAT and pacing from the multiple sites in RA shown by 3D mapping. P wave paced match score and deviation of paced activation sequence from clinical FAT are shown under each 12-lead ECG. Best paced match obtained at high CT (11/12 leads). **B,** The activation sequence of clinical FAT induced during the procedure (**left**) is identical to paced activation sequence obtained from His proximal and CS 1 to 2 during sinus rhythm at high CT (**right**). 3D indicates 3-dimensional; CS, coronary sinus; CT, crista terminalis; FAT, focal atrial tachycardia; FW, free wall; RA, right atrium; and TA, tricuspid annulus.

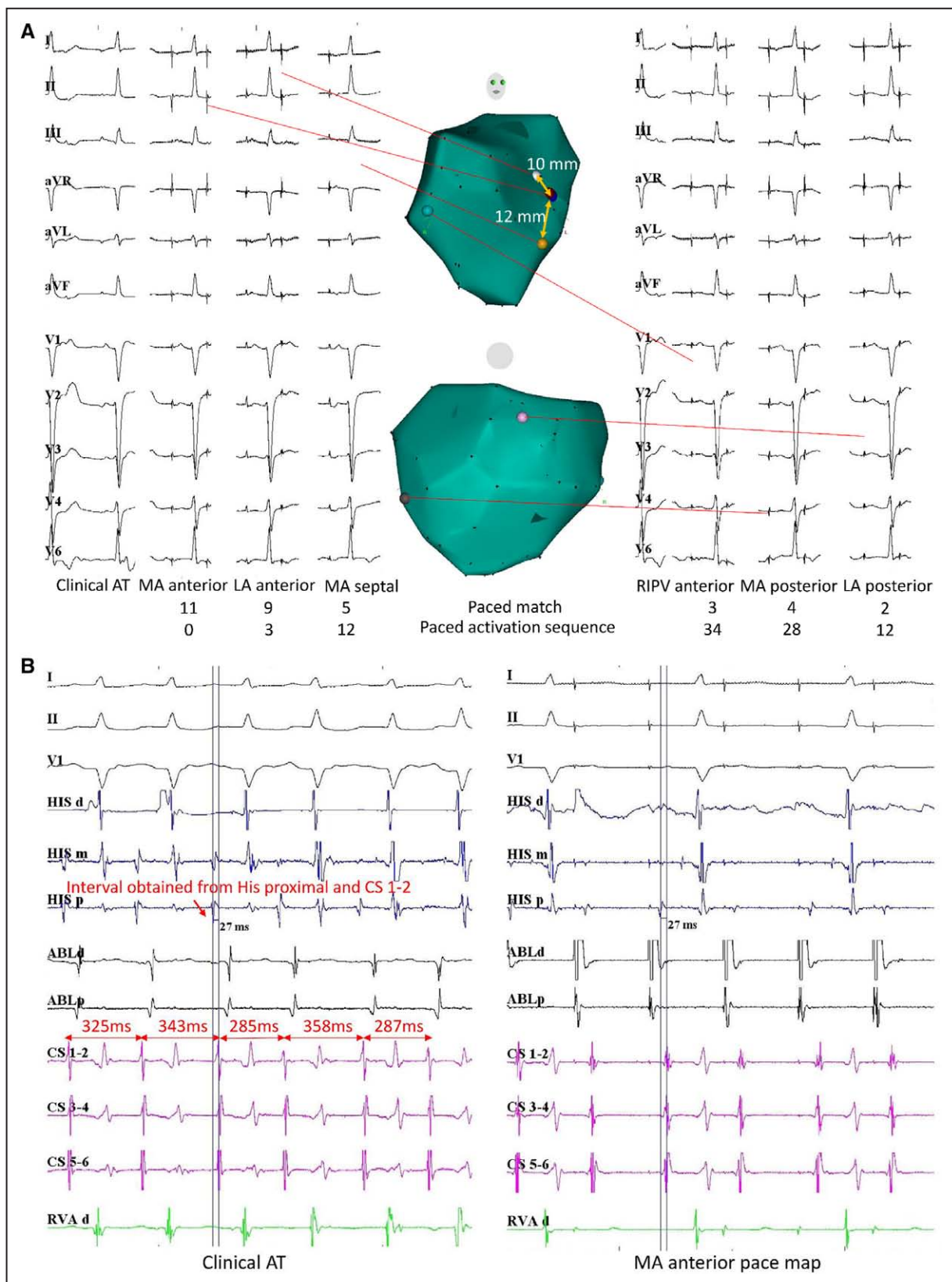


Figure 3. A, (Patient no 2): Comparison of the P wave morphology during FAT and pacing from the multiple sites in LA shown by 3D mapping. P wave paced match score and deviation of paced activation sequence from clinical FAT are shown under each 12-lead ECG. Best paced match obtained at anterior MA (11/11 leads). Because of noise in V5, we obtained only 11 leads. **B**, The activation sequence of clinical FAT induced during the procedure (**left**) is identical to paced activation sequence obtained from His proximal and CS 1 to 2 during sinus rhythm at anterior MA (**right**). 3D indicates 3-dimensional; AT, atrial tachycardia; CS, coronary sinus; FAT, focal atrial tachycardia; LA, left atrium; MA, mitral isthmus; and RIPV, right inferior pulmonary vein.

the right inferior PV (patient no 7). At the best-paced site, the paced P wave morphology on 12-lead ECG was matched to the clinical P wave morphology in 12/12 leads (patient no 7) and in 11/12 leads (patients no 3 and no 4; Figure 4A); no significant delay from stimulus to P wave onset was observed. Paced intracardiac activation sequence obtained from CS and His/PV catheter was the same as the sequence of the clinical FAT, and the deviation from the clinical tachycardia was 0 ms in all 3 patients (Figure 4B). In patient no 5 with previous PVI, pacing within the right superior PV and at the conduction gap located in the middle of the previous posterior linear lesion demonstrated the best match to the clinical P wave morphology. No significant delay from stimulus to P wave onset was observed by pacing at the conduction gap, whereas a long delay from stimulus to P wave onset (140 ms) on pacing from the Lasso catheter within the right superior PV was shown (Figure 5).

The P wave morphology of the anterior right inferior PV origin (patient no 3) was biphasic (positive–negative) in lead V1 and flat in lead aVL, whereas in 3 patients with right-sided posterior and inferior PV origin (patients no 4, no 5, and no 7), the P wave during tachycardia and PM demonstrated a clear M wave (bifid positive) in lead V1 and a biphasic (positive–negative) P wave in lead aVL (patient no 4), flat-positive P wave in lead aVL (patient no 5), and negative P wave in aVL (patient no 7).

The mean PM time during the procedure was 26.9 ± 5.7 minutes. After identifying the best-paced site, a nonsustained FAT with a maximal duration of 2 s was induced only in patients no 3 and no 4. The earliest local activation was found at the best-paced site and preceded the P wave onset by 40 ms (patient no 3) and 25 ms (patient no 4).

Not lower than 11/12 P wave–paced match identified FAT origins with a sensitivity of 100% and specificity of 100%. The deviation of paced intracardiac activation sequence from the clinical tachycardia of <5 ms identified FAT origins with a sensitivity of 100% and specificity of 78%.

The minimal distance between the best-paced match site and the site with at least 1 lead different paced P wave morphology measured in the 3D mapping system was 9 to 13 mm in each patient.

CA and Follow-Up

In the 3 patients with non-PV origin (patients no 1, no 2, and no 6), 2 or 3 radiofrequency applications with a total duration of 180 to 240 s were delivered at the best-paced site because of noninducibility after extensive mapping. Radiofrequency-associated response occurred only in patient no 1 in whom the radiofrequency ablation–induced tachycardia with a fast CL, similar P wave, and atrial activation suddenly disappeared 6 s after ablation.

In 3 patients with PV origin and without previous PVI (patients no 3, no 4, and no 7), circumferential RPI was performed. A total of 9 to 12 RF applications with 610 to 820 s resulted in complete PVI with entrance and exit block. In 1 patient with previous PVI (patient no 5), a single radiofrequency application with a duration of 120 s was delivered at the conduction gap and resulted in complete electric isolation of RPV. Nonconducted PV tachycardia from variable CL

within the isolated PVs was observed during radiofrequency ablation in these 4 patients.

The mean procedure time and fluoroscopy time was 110 ± 13.8 and 5.9 ± 5.4 minutes, respectively. The cumulative delivered energy was 5732 to 6970 J in patients with non-PV origin FAT, 21 342 to 27 342 J in patients with PV-origin FAT, and 3538 J in patient with FAT because of conduction gap of PVI.

No FATs were induced at the end of the procedure even using isoproterenol infusion and pacing maneuvers, and no complications occurred. There were no AT-associated symptoms and no evidence of atrial arrhythmias on multiple recordings from surface ECG (3–6 times) and three 24-hour Holter ECG. All patients were free of arrhythmias without AADs during the follow-up of 8.4 ± 5.6 months.

Discussion

The basic prerequisite for FAT ablation is to identify the earliest site of intracardiac activation using conventional or 3D mapping techniques. However, it is clinically difficult to map and ablate difficult-to-induce and nonsustained FAT with and without the intravenous administration of isoproterenol. Furthermore, mechanical interruption by endocardial catheters occasionally causes tachycardia suppression.⁹ The P wave algorithm clinically facilitates localization of the tachycardia origin in patients with normal hearts,^{4–8} but it is occasionally inaccurate. Our PM method may complement the weakness of P wave algorithm and provide some clinical implication and usefulness for specific patients.

P Wave Morphology in 12-Lead ECG and Distribution of FAT

FAT origins in RA occur along crista terminalis,¹⁰ tricuspid annulus,¹¹ the ostium of CS,¹² and the perinodal region. In LA, origins occur predominantly at the PV ostia^{4,7,13} and mitral annulus^{7,14} and less commonly in the LA appendage¹⁵ and left-sided septum. The specific anatomic location can provide a unique P wave on 12-lead ECG. Leads aVL and V1 have been described as the best for distinguishing between LA and RA foci,^{5,6,16} and the P wave morphological algorithm can help identify the FAT origin. Several predictors have been reported, and 2 algorithms clinically developed by Kistler et al⁵ and Tang et al⁶ are commonly used. Kistler et al provided a detailed analysis of the utility of P wave configuration for localization of FAT origins using lead V1, lead aVL, and inferior leads. Tang et al stated that leads aVL and V1 were most helpful in distinguishing RA from LA foci. The FAT origins were identified using Kistler's algorithm in the 3 patients with non-PV origins and in 1 of the 4 patients with PV origins. All FATs because of the RPV posterior site in our study showed an M wave (bifid positive), which is incompatible with Kistler's algorithm that the P wave in V1 showed monofid-positive P wave in V1 on surface ECG. The activation sequence of FAT from posterior RPV is different compared with that from anterior RPV. Kistler's study probably included many patients with FAT from anterior RPV; therefore, the P wave of our patients did not fit into his algorithm, and our study included 3 posterior RPV FAT. The difference from Kistler's algorithm can be explained: (1) FAT from RPV mostly originates from the anterior wall of RPV, which simultaneously

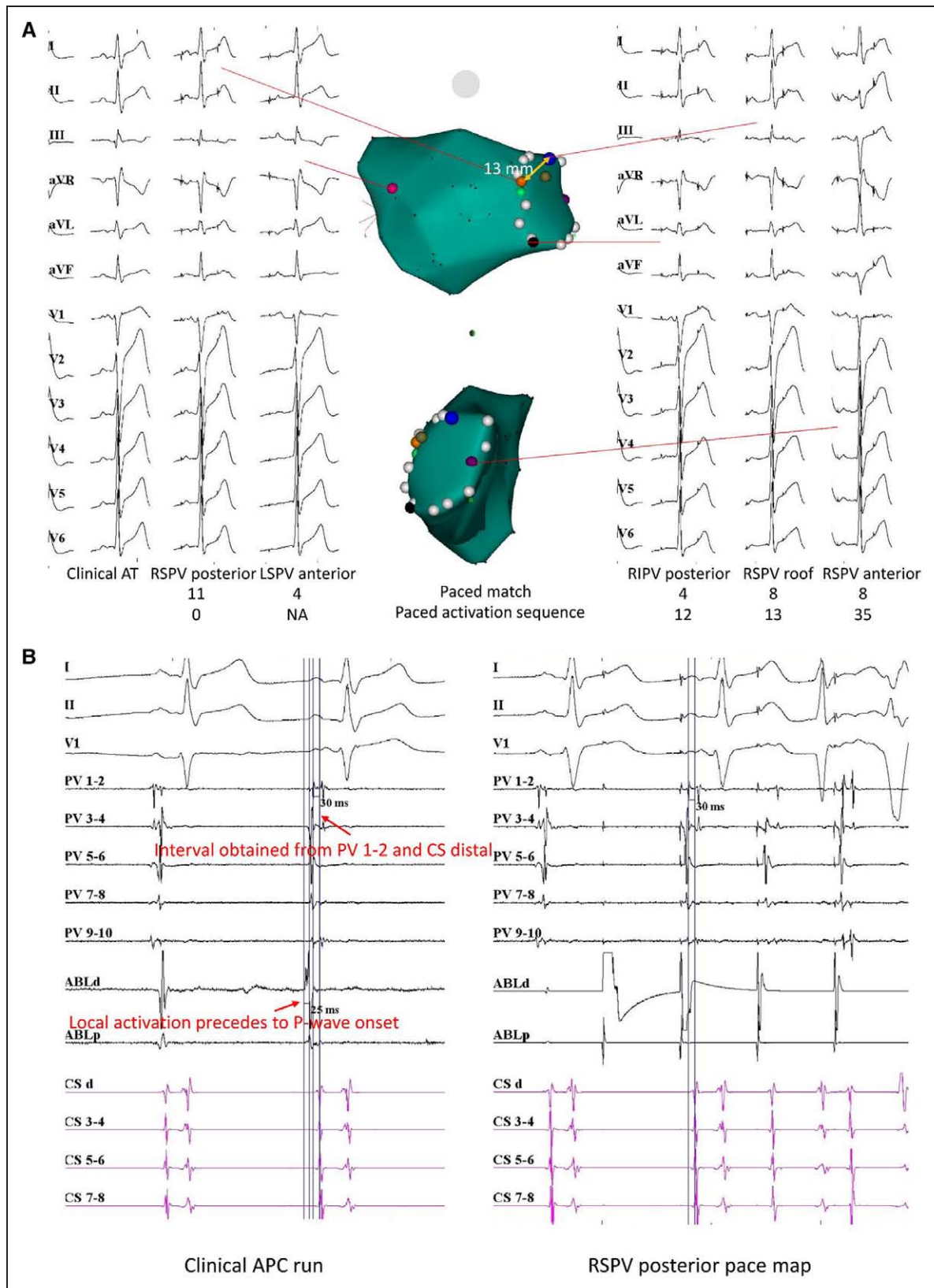


Figure 4. A, (Patient no 4): Comparison of the P wave morphology during FAT and pacing from the multiple sites in LA shown by 3D mapping. P wave paced match score and deviation of paced activation sequence from clinical FAT are shown under each 12-lead ECG. Best paced match obtained at anterior RSPV posterior (11/12 leads). **B,** The activation sequence of clinical FAT induced during procedure (left panel) is identical to paced activation sequence obtained from PV 1 to 2 and CS distal during sinus rhythm at RSPV posterior (right). The local atrial activation preceded the P wave onset by 25 ms during induced FAT (left). 3D indicates 3-dimensional; AT, atrial tachycardia; CS, coronary sinus; FAT, focal atrial tachycardia; LA, left atrium; LSPV, left superior pulmonary vein; RIPV, right inferior pulmonary vein; and RSPV, right superior pulmonary vein.

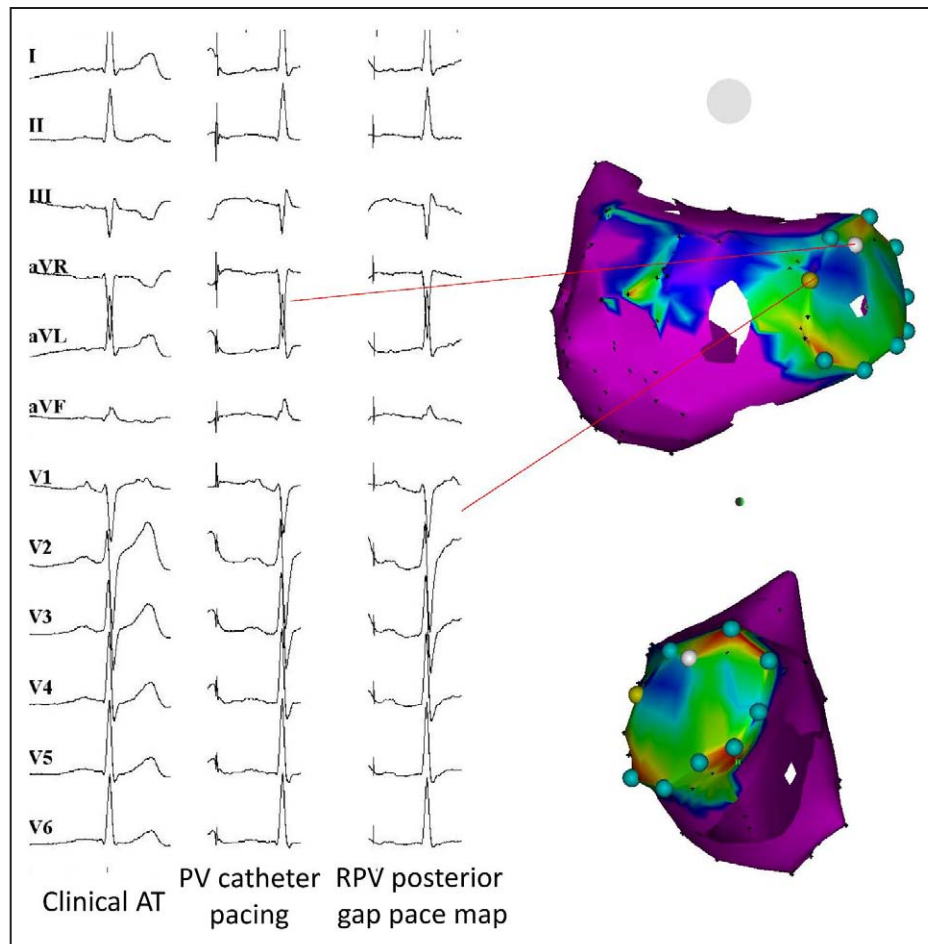


Figure 5. (Patient no 5): Comparison of the P wave morphology during FAT and pacing from the 2 sites in LA shown by 3D voltage mapping. Pacing within RSPV and at the conduction gap located in the middle of the previous linear lesion demonstrated a best match of P wave morphology. No delay from stimulus to P wave onset was observed by pacing at the conduction gap, and a long delay was observed by pacing inside RSPV. 3D indicates 3-dimensional; AT, atrial tachycardia; FAT, focal atrial tachycardia; LA, left atrium; PV, pulmonary vein; RSPV, right superior pulmonary vein.

activates LA and RA via Bachman's bundle and produces monofid P wave in V1; and (2) the origin from posterior wall of RSPVs propagate from LA posterior wall to LA anterior wall and then propagate to RA, which creates a bifid-positive morphology in V1 in our patients. Additionally, in 3 patients with FAT from posterior antrum of the right-sided PV, bifid P wave in V1 was similar to that originating from the left-sided PVs. However, polarity of the P wave in lead I can differentiate them. Furthermore, the P wave algorithm developed by Tang et al also was compatible in 4/7 patients. These algorithms are based on the normal atrial muscle. However, in cases of low-voltage or conduction block areas in the atrium because of CA or surgical operation, the conduction sequence in the atrium differs from that of the normal heart.

P Wave and Intracardiac Activation Sequence During PM

PM of P waves is difficult because of the low P wave amplitude and superimposition of the P wave on T wave during tachycardia. We could evaluate the P waves preceded by an isoelectric baseline because of variable CL during clinical tachycardia in all cases. Selvaraj et al reported the accuracy of

manual P wave PM.¹⁷ They indicated that paced match score at the same paced site was 11.5 ± 0.6 out of 12 for the 12-lead ECG evaluated by blinded observer. This result supports P wave pacing methodology.

Man et al.¹⁸ assessed the spatial resolution of P wave morphology using unipolar atrial PM at different CS and RA-free wall sites. They demonstrated that only subtle changes in P wave morphology occur when atrial pacing sites are 11 to 17 mm apart. In another study, the spatial resolution of PM in atrium using unipolar pacing was 9.9 mm.¹⁷ Although significant changes in P wave amplitude and duration can be detected, the magnitudes are small and often visually indiscernible. However, FAT usually originates from particular complex structures (eg, crista terminalis, PVs, CS ostium, and around the annulus). P wave configuration could easily vary in these areas because of the complexity of atrial conduction from FAT origins relative to that of uniform structures, as mentioned in previous reports (eg, the CS middle part and RA-free wall). Bipolar PM with minimal output showed different P wave morphologies within 9 to 13 mm between non-uniform structures and provided a useful supplementary guide to the location of the FAT origin (Figures 2A–4A). Kadish

et al examined differences in QRS configuration produced by bipolar versus unipolar pacing.¹⁹ They indicated that only minor QRS configuration differences (0.5 ± 1.2 leads) between unipolar and bipolar pacing occurred when the interelectrode distance during bipolar pacing was 5 mm; however, when the interelectrode distance was 10 mm, this difference was more obvious (1.3 ± 2.0 leads). We used mapping catheter with 2-mm interelectrode distance for bipolar pacing; therefore, bipolar pacing in our study resulted in similar spatial resolution compared with unipolar pacing reported previously.

However, to complement the spatial limitations of P wave PM, more information about atrial activation sequence during PM is required. Paced intracardiac activation sequence in combination with P wave PM may be helpful to complete difficult-to-induce and nonsustained FAT localization. Tracy et al used a paced intracardiac activation sequence and compared the activation sequence at multiple atrial sites during spontaneous tachycardia with that recorded using multiple catheters and the ablation catheter.¹ Using this technique and activation mapping, Tracy et al reported a success rate of 80% without 3D mapping, wherein significantly less deviation from the spontaneous activation sequences occurred (2 ± 2 ms, range: 0–5) at the sites of successful energy delivery relative to that at the sites of unsuccessful energy delivery. The matched paced intracardiac activation sequence correlated with the earlier activation time recorded using the ablation catheter that preceded the earliest intracardiac atrial activation or the earliest surface ECG P wave. Ju et al reported mapping of FAT or localized reentry of tachycardia with a chaotic activation map because of intra-atrial conduction delay after extensive atrial ablation.²⁰ Santangeli et al reported that analysis of implantable cardioverter defibrillator electrogram morphology with pacing around the edge of the scar was unable to distinguish distinct ventricular tachycardia exit sites spaced <2 cm apart.²¹ These 2 reports indicate the difficulty in evaluation of P wave and intracardiac activation sequences during PM with diseased atrial muscle. We always tried to pace with minimal output and CL similar to clinical AT to avoid far-field capture and increment of intra-atrial conduction delay. Theoretically, the PM method is available in patients with diseased atrial muscle. However, in our study, only 2 patients with large scar areas in LA were included, and both were FAT from PV. Therefore, further evaluation is required to verify this method in patients with low-voltage areas and FAT originating from outside PV. In our patients with previous circumferential PVI, PM at the conduction gap and within the RPVs demonstrated the same P wave (Figure 5) and identical activation sequence. This technique can help identify the recovered conduction across the previous wide circumferential PVI and facilitate ablation procedure of difficult-to-induce AT because of focal tachycardia from PV.

CA of FAT

Previous studies have demonstrated that a noncontact mapping system could be used for mapping and ablating nonsustained FAT.^{22,23} However, the noncontact mapping system is highly dependent on the anatomic distance between the origin and balloon location. Moreover, interpretation of virtual noncontact electrograms is difficult and may be influenced by individual investigators. Completion of mapping is impossible if

clinical AT cannot be induced after positioning of the system in the atrium area of interest. In our study, P wave PM and paced intracardiac activation sequence mapping can solve these problems. It was further supported with clinical outcome during follow-up in our patients with frequent nonsustained FAT.

Limitations

This study had several limitations. First, a major limitation of this study was the small number of enrolled patients (6.1% of focal AT) because we used the pacing maneuver only for a subset of patients with difficult-to-induce and nonsustained AT. In particular, the utility of PM in patients with structural atrial disease remains to be determined and should be verified in a larger number of patients for generalized application. Second, because of lack of specific software to evaluate P wave morphology (eg, PaSo module; Biosense Webster or EnSite Precision software; St Jude Medical), qualitative measurement of P wave morphology was systematically performed. A much larger number of patients or more precise quantitative analysis is needed to verify this technique. However, the clinical results of successful ablation in all patients are encouraging. Third, in keeping with the known spatial limitations of P wave PM, anatomic sites in close proximity may be more difficult. Therefore, patients with difficult-to-induce tachycardia theoretically require a relatively wide ablation area. However, only a few radiofrequency applications can eliminate clinical ATs in patients with non-PV origins in clinical practice. Finally, P wave PM cannot be used if the P wave is unclear, despite using vagal maneuver, infusion of adenosine, or termination of ventricular pacing.

Conclusions

PM may be useful for identifying the FAT origins by matching P wave morphology and intracardiac atrial activation sequence. This maneuver can be used for patients with difficult-to-induce and nonsustained FAT.

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Disclosures

None.

References

1. Tracy CM, Swartz JF, Fletcher RD, Hoops HG, Solomon AJ, Karasik PE, Mukherjee D. Radiofrequency catheter ablation of ectopic atrial tachycardia using paced activation sequence mapping. *J Am Coll Cardiol*. 1993;21:910–917.
2. Chen SA, Chiang CE, Yang CJ, Cheng CC, Wu TJ, Wang SP, Chiang BN, Chang MS. Sustained atrial tachycardia in adult patients. Electrophysiological characteristics, pharmacological response, possible mechanisms, and effects of radiofrequency ablation. *Circulation*. 1994;90:1262–1278.
3. Blomström-Lundqvist C, Scheinman MM, Alpert EM, Alpert JS, Calkins H, Camm AJ, Campbell WB, Haines DE, Kuck KH, Lerman BB, Miller DD, Shaeffer CW, Stevenson WG, Tomaselli GF, Antman EM, Smith SC Jr, Alpert JS, Faxon DP, Fuster V, Gibbons RJ, Gregoratos G, Hiratzka LF, Hunt SA, Jacobs AK, Russell RO Jr, Priori SG, Blanc JJ, Budaj A, Burgos EF, Cowie M, Deckers JW, Garcia MA, Klein WW, Lekakis J, Lindahl B, Mazzotta G, Morais JC, Oto A, Smiseth O, Trappe HJ; European Society of Cardiology Committee, NASPE-Heart Rhythm Society. ACC/AHA/

- ESC guidelines for the management of patients with supraventricular arrhythmias—executive summary. a report of the American college of cardiology/American heart association task force on practice guidelines and the European society of cardiology committee for practice guidelines (writing committee to develop guidelines for the management of patients with supraventricular arrhythmias) developed in collaboration with NASPE-Heart Rhythm Society. *J Am Coll Cardiol.* 2003;42:1493–1531.
4. Yamane T, Shah DC, Peng JT, Jais P, Hocini M, Deisenhofer I, Choi KJ, Macle L, Clémenty J, Haïssaguerre M. Morphological characteristics of P waves during selective pulmonary vein pacing. *J Am Coll Cardiol.* 2001;38:1505–1510.
 5. Kistler PM, Roberts-Thomson KC, Haqqani HM, Fynn SP, Singarayer S, Vohra JK, Morton JB, Sparks PB, Kalman JM. P-wave morphology in focal atrial tachycardia: development of an algorithm to predict the anatomic site of origin. *J Am Coll Cardiol.* 2006;48:1010–1017. doi: 10.1016/j.jacc.2006.03.058.
 6. Tang CW, Scheinman MM, Van Hare GF, Epstein LM, Fitzpatrick AP, Lee RJ, Lesh MD. Use of P wave configuration during atrial tachycardia to predict site of origin. *J Am Coll Cardiol.* 1995;26:1315–1324. doi: 10.1016/0735-1097(95)00307-X.
 7. Hachiya H, Ernst S, Ouyang F, Mavrakis H, Chun J, Bänsch D, Antz M, Kuck KH. Topographic distribution of focal left atrial tachycardias defined by electrocardiographic and electrophysiological data. *Circ J.* 2005;69:205–210.
 8. Huo Y, Braunschweig F, Gaspar T, Richter S, Schönbauer R, Sommer P, Arya A, Rolf S, Bollmann A, Hindricks G, Piorkowski C. Diagnosis of atrial tachycardias originating from the lower right atrium: importance of P-wave morphology in the precordial leads V3–V6. *Europace.* 2013;15:570–577. doi: 10.1093/europace/eus314.
 9. Chiang CE, Chen SA, Wu TJ, Yang CJ, Cheng CC, Wang SP, Chiang BN, Chang MS. Incidence, significance, and pharmacological responses of catheter-induced mechanical trauma in patients receiving radiofrequency ablation for supraventricular tachycardia. *Circulation.* 1994;90:1847–1854.
 10. Kalman JM, Olgin JE, Karch MR, Hamdan M, Lee RJ, Lesh MD. “Cristal tachycardias”: origin of right atrial tachycardias from the crista terminalis identified by intracardiac echocardiography. *J Am Coll Cardiol.* 1998;31:451–459.
 11. Morton JB, Sanders P, Das A, Vohra JK, Sparks PB, Kalman JM. Focal atrial tachycardia arising from the tricuspid annulus: electrophysiologic and electrocardiographic characteristics. *J Cardiovasc Electrophysiol.* 2001;12:653–659.
 12. Kistler PM, Fynn SP, Haqqani H, Stevenson IH, Vohra JK, Morton JB, Sparks PB, Kalman JM. Focal atrial tachycardia from the ostium of the coronary sinus: electrocardiographic and electrophysiological characterization and radiofrequency ablation. *J Am Coll Cardiol.* 2005;45:1488–1493. doi: 10.1016/j.jacc.2005.01.042.
 13. Kistler PM, Sanders P, Fynn SP, Stevenson IH, Hussin A, Vohra JK, Sparks PB, Kalman JM. Electrophysiological and electrocardiographic characteristics of focal atrial tachycardia originating from the pulmonary veins: acute and long-term outcomes of radiofrequency ablation. *Circulation.* 2003;108:1968–1975. doi: 10.1161/01.CIR.0000095269.36984.75.
 14. Wang Y, Li D, Zhang J, Han Z, Ren X, Li X, Chen F. Focal atrial tachycardia originating from the septal mitral annulus: Electrocardiographic and electrophysiological characteristics and radiofrequency ablation. *Europace.* 2015. pii: euv256. [Epub ahead of print]. doi: 10.1093/europace/euv256.
 15. Yang Q, Ma J, Zhang S, Hu JQ, Liao ZL. Focal atrial tachycardia originating from the distal portion of the left atrial appendage: characteristics and long-term outcomes of radiofrequency ablation. *Europace.* 2012;14:254–260. doi: 10.1093/europace/eur302.
 16. Kistler PM, Kalman JM. Locating focal atrial tachycardias from P-wave morphology. *Heart Rhythm.* 2005;2:561–564. doi: 10.1016/j.hrthm.2004.12.013.
 17. Selvaraj RJ, Yerram S, Kumar P, Satheesh S, Pillai AA, Saktheeswaran MK, Balachander J. Pace mapping in the atrium using bipolar electrograms from widely spaced electrodes. *J Arrhythm.* 2015;31:274–278. doi: 10.1016/j.joa.2015.02.002.
 18. Man KC, Chan KK, Kovack P, Goyal R, Bogun F, Harvey M, Daoud E, Strickberger A, Morady F. Spatial resolution of atrial pace mapping as determined by unipolar atrial pacing at adjacent sites. *Circulation.* 1996;94:1357–1363.
 19. Kadish AH, Schmaltz S, Morady F. A comparison of QRS complexes resulting from unipolar and bipolar pacing: implications for pace-mapping. *Pacing Clin Electrophysiol.* 1991;14(5 pt 1):823–832.
 20. Ju W, Yang B, Chen H, Zhang F, Gu K, Yu J, Li M, Yang G, Cao K, Chen M. Mapping of focal atrial tachycardia with an uninterpretable activation map after extensive atrial ablation: tricks and tips. *Circ Arrhythm Electrophysiol.* 2014;7:598–604. doi: 10.1161/CIRCEP.114.001508.
 21. Santangeli P, Alcalde O, Zado ES, Callans DJ, Marchlinski FE. Spatial resolution of defibrillator electrograms to detect distinct exit sites of scar-related ventricular tachycardia. *Pacing Clin Electrophysiol.* 2014;37:1256–1264. doi: 10.1111/pace.12444.
 22. Hindricks G, Kottkamp H. Simultaneous noncontact mapping of left atrium in patients with paroxysmal atrial fibrillation. *Circulation.* 2001;104:297–303.
 23. Wiecek M, Salili AR, Kaubisch S, Hoeltgen R. Catheter ablation of non-sustained focal right atrial tachycardia guided by virtual non-contact electrograms. *Europace.* 2011;13:876–882. doi: 10.1093/europace/eur058.

Pace Mapping for the Identification of Focal Atrial Tachycardia Origin: A Novel Technique to Map and Ablate Difficult-to-Induce and Nonsustained Focal Atrial Tachycardia

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